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THESIS

STATISTICAL ANALYSIS OF WIRELESS NETWORKING: PREDICTING PERFORMANCE IN MULTIPLE ENVIRONMENTS

by

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June 2006

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With the advent of easily accessible, deployable, and usable 802.11 technology, users can connect and network with practically any infrastructure that exists today. Due to that simplicity and ease of use, it only seems logical that the military and tactical users should also employ these technologies.

The questions regarding 802.11 network performances in a hostile and signal-unfriendly environment (i.e., high temperature and high humidity) have yet to be answered. The goal of this thesis is to quantify 802.11 network capabilities, in terms of throughput, while it is employed in those areas. Ultimately, the objective is to produce statistical models able to represent any variations in the 802.11 signals and network due to those environmental factors.

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A STATISTICAL ANALYSIS OF WIRELESS NETWORKING; PREDICTING PERFORMANCE IN MULTIPLE ENVIRONMENTS

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With the advent of easily accessible, deployable, and usable 802.11 technology, users can connect and network with practically any infrastructure that exists today. Due to that simplicity and ease of use, it only seems logical that the military and tactical users should also employ these technologies.

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LIST OF ABBREVIATIONS / ACRONYMS

IEEE	Institute of Electrical and Electronics Engineers
WLAN	Wireless Local Area Network
COTS	Commercial Off the Shelf
COASTS	Coalition Operating Surveillance and Targeting System
NPS	Naval Postgraduate School
NPSSOCFEP	NPS-U.S. Special Operations Command Field Experimentation Program
USSOCOM	U.S. Special Operations Command
FY	Fiscal Year
SOF	Special Operations Forces
DoD	Department of Defense
TTP’s	Techniques/tactics/procedures
FLAK	Fly-Away Kit
SSA	Shared Situational Awareness
UAV	Unmanned Aerial Vehicle
OFDM	Orthogonal Frequency Division Multiplexing
SATCOM	Satellite Communications
PNM	Personal Navigation Manager
AO	Area of Operations
WWW	World Wide Web
CC	Control Center
RTAF	Royal Thai Air Force
IIFC	Interagency Information Fusion Center

MIFC	Maritime Information Fusion Center
GHz	Giga-Hertz
Wi-Fi	Wireless Fidelity
VoIP	Voice over Internet Protocol
TOC	Tactical Operations Center
SOSUS	Sound Surveillance System
FHL	Fort Hunter Liggett
LOS	Line of Sight
NMS	Network Management Software
Mbps	Mega-bytes per second
GUI	Graphical User Interface

EXECUTIVE SUMMARY

In this thesis, the use of a standard 802.11g wireless signal in a signal hostile and unfriendly (i.e., high temperature, high humidity) environment is analyzed. Since the goal of the research project is to demonstrate the feasibility and use of commercially available products in a tactical and operational manner, the effects that might occur between environmental factors (temperature, humidity, pressure, etc) and the 802.11 signal are analyzed, specifically to see if the signal throughput is affected at all in the presence of these factors. The analysis attempts to identify any types of interactions that are occurring, and if those interactions have a positive or negative affect on throughput. In addition, the analysis reveals what kind of losses, if any, can be expected in different environments.

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I. INTRODUCTION

A. BACKGROUND

The continuing development of the Institute of Electrical and Electronics Engineers (IEEE) wireless 802.11 networking standard in the world today has given the average person commercially available, inexpensive wireless technology. This is turn permits easy and rapid connection to an existing 802.11 wireless local area network (WLAN). Using these connections, an individual can surf the internet at the local coffee shop, check email while in line at the supermarket and even buy stock while at the car wash. What has caused this proliferation in easily accessible WLANs is not the fact that the technology is extremely wide-reaching but that it is a relatively simple system to set up and then deploy.

Wireless networking in itself is not a new idea. While in a different sense than the way the word is used today, a connection between two handheld radios can be identified as a version of wireless networking. In this case, data is being passed in the form of voice communications. However, with the rise of 802.11 networking technology, there has been a vast increase in the amount of data that can be passed as well as the speeds at which that data travels between the users on either end.

Combined with the ease of usage that is inherent and has been routinely demonstrated in 802.11, capabilities exist that may potentially assist the warfighter during operations in a tactical environment. The greater flow of accurate data provides the warfighter with better spatial and situational awareness thereby giving him the tools needed for more effectively combating the enemy. If a unit is preparing for a specific mission the use of a local WLAN will not only reduce the infrastructure needed for communications but increase the amount and types of data that can quickly and easily be relayed to the combatant commanders, giving them more flexibility in directing a unit’s response to an incident.

B. THE TACTICAL USER

Through a combination of existing commercial off the shelf (COTS) technologies, an 802.11 network can be rapidly constructed for tactical use. The elements that exist can extend to cover the following areas:

- Ground Vehicles
- Lighter than Air Vehicles
- Unmanned Aerial Vehicles
- Individual Soldiers.

Each one of the aforementioned elements may be configured so they can mesh with 802.11 technology. Utilizing these different elements provides a greater networking signal footprint, thereby extending the command and control that the combatant commander can provide. As such, there is a greater flow of data from the battlefield to the unit commander and, if needed, to the mission level or even theatre level commander.

However, the field is an environment that is harsh and unforgiving. A deployment of existing COTS 802.11 technology requires a robust platform that can withstand the ever-changing environmental conditions that may be experienced throughout the world. Fortunately, the commercial world has realized the need for these robust platforms and has produced strong equipment capable of handling the most extreme environmental situations.

C. COASTS 2006

1. Background

The Coalition Operating Area Surveillance and Targeting System (COASTS) programmatic concept is modeled after a very successful ongoing Naval Postgraduate School (NPS)-driven field experimentation program entitled the NPS-U.S. Special Operations Command Field Experimentation Program (NPSSOCFEP). NPSSOCFEP is executed by NPS, in cooperation with the U.S. Special Operations Command (USSOCOM) and several contractors, and has been active since Fiscal Year (FY) 2002. Program inception supported USSOCOM requirements for integrating emerging WLAN technologies with surveillance and targeting hardware and software systems to augment Special Operations Forces (SOF) missions. NPSSOCFEP has grown significantly since inauguration to include approximately ten private sector companies who continue to demonstrate their hardware and software capabilities, several NPS-led Department of Defense (DoD) organizations who provide operational and tactical surveillance and targeting requirements, and other academic institutions and universities who contribute a variety of resources[1].

Unfortunately, certain hardware, software, and tactics, techniques, and procedures (TTP's) implemented at NPSSOCFEP are classified or operationally sensitive and as a result sponsors have not agreed to foreign military partnerships. However, DoD requires that U.S. military forces operate in coalition environments, which serve to strengthen relationships with foreign military partners and to execute missions globally. Since NPSSOCFEP remains primarily US-only, COASTS was designed to address coalition inter-operability exchange and cooperative research and development[2].

2. Purpose

COASTS 2006 will expand upon the original field experiment conducted during last year's deployment to Wing 2, Lop Buri, Thailand. This year the network topology will research equipment relative to low-cost, commercially available solutions while integrating each technology and capability into a larger system of systems in support of tactical action scenarios.

The demonstration planned for May 2006 is an air, ground, and water-based scenario, occurring just north of Chiang Mai, Thailand. The scenario encompasses first-responder, law enforcement, counter-terrorism, and counter-drug objectives. The tactical information being collected from the scenario will be fused, displayed, and distributed in real-time to local (Chiang Mai), theater (Bangkok), and global (Alameda, California) command and control (C2) centers. This fusion of information will lead to the validation of using wireless

[1] COASTS 2006 CONOPS, p.1

[2] Ibid., p.3

communication mediums to support redundant links of the National Information Infrastructure, as well as to test and evaluate the 'last mile' solution for the disadvantaged user.

Continuing with last year's research theme, COASTS 2006 will again: (1) examine the feasibility of rapidly-deploying networks, called "Fly-away Kits" (FLAK) and (2) explore sustainable considerations with respect to a hostile climatic (temperature, humidity, wind, etc.) environment. Network improvements will include the testing and evaluation of new 802.11 mesh WLAN equipment, the refinement of a jointly-developed (NPS and Mercury Data Systems) 3-D topographic shared situational awareness (SSA) application called C3Trak, the integration of "satellite in a suitcase" (portable satellite communication equipment) technology, enhanced unattended ground and water-based sensors, new balloon and unmanned aerial vehicles (UAV) designs, portable biometric devices, portable explosive residue detecting devices, and revised operational procedures for deployment of the network[3].

3. COASTS Tactical Implementation

Through the use of all of the elements involved with the COASTS experiment the final objective is that the soldier or unit on the ground has complete spatial awareness of his specific battlespace. Using a rapidly deployable WLAN mesh network, the objective is that the user can integrate into the network via several different methods which would include:

- 802.11b/g
- 802.16 Orthogonal Frequency Division Multiplexing (OFDM)
- Satellite Communications (SATCOM)
- Situational Awareness Software
- Wearable Computing Devices
- Personal Navigation Monitors (PNM)
- Air and Ground Sensors
- Mobile/Fixed Command and Control Platforms.

[3] COASTS 2006 CONOPS, pp. 3-4

All of these different methods would mesh seamlessly so the user could identify, communicate, and ultimately operate with the other units on the ground as well as remain in contact with the commanders removed from the battlefield and even commanders who are removed from the theatre.

The end objective for the overall COASTS project is that through the use of modern technology the maximum amount of force can be brought to bear while providing the maximum amount of battlefield awareness and using the smallest amount of support.

D. THESIS OBJECTIVES

The COASTS 2006 field experiment is utilizing various advances in 802.11 technology that will permit a rapidly formed mesh network via COTS equipment. In addition, the area of operations (AO) is an environmentally hostile location so the equipment being employed has been designed to withstand the hostile conditions expected. However, what has not been examined in detail is the effect that the varying environmental factors might have on the 802.11 signal.

The goal of this thesis is to build upon pre-existing models of an 802.11 signal in an urban, signal-friendly setting. Data gathered from the wireless 802.11 network in a tactical and operational situation will help to increase the understanding of how an 802.11 signal will operate in those types of hostile environments. Using commercial networking analysis software as well as statistical and regression packages, models will be constructed that will demonstrate the effect of the diverse environmental factors on the wireless signal. The ultimate goal is to provide following iterations of COASTS as well as other coalition partners a method of predicting future performance of an 802.11 network in multiple environmental conditions.

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II. THE TACTICAL ENVIRONMENT

A. COASTS 2006 TOPOLOGY

The 2006 version of the COASTS project occurred just north of Chiang Mai, Thailand, at the Mae Ngat Dam. COTS systems were utilized allowing for a rapid deployment of the network and all associated nodes. Once deployed, each node was capable of joining the wireless mesh created and permitted the passing of information between all of the individual nodes.

Figure 1 and Figure 2 below show the global network topology as well as the local Thailand network topology.

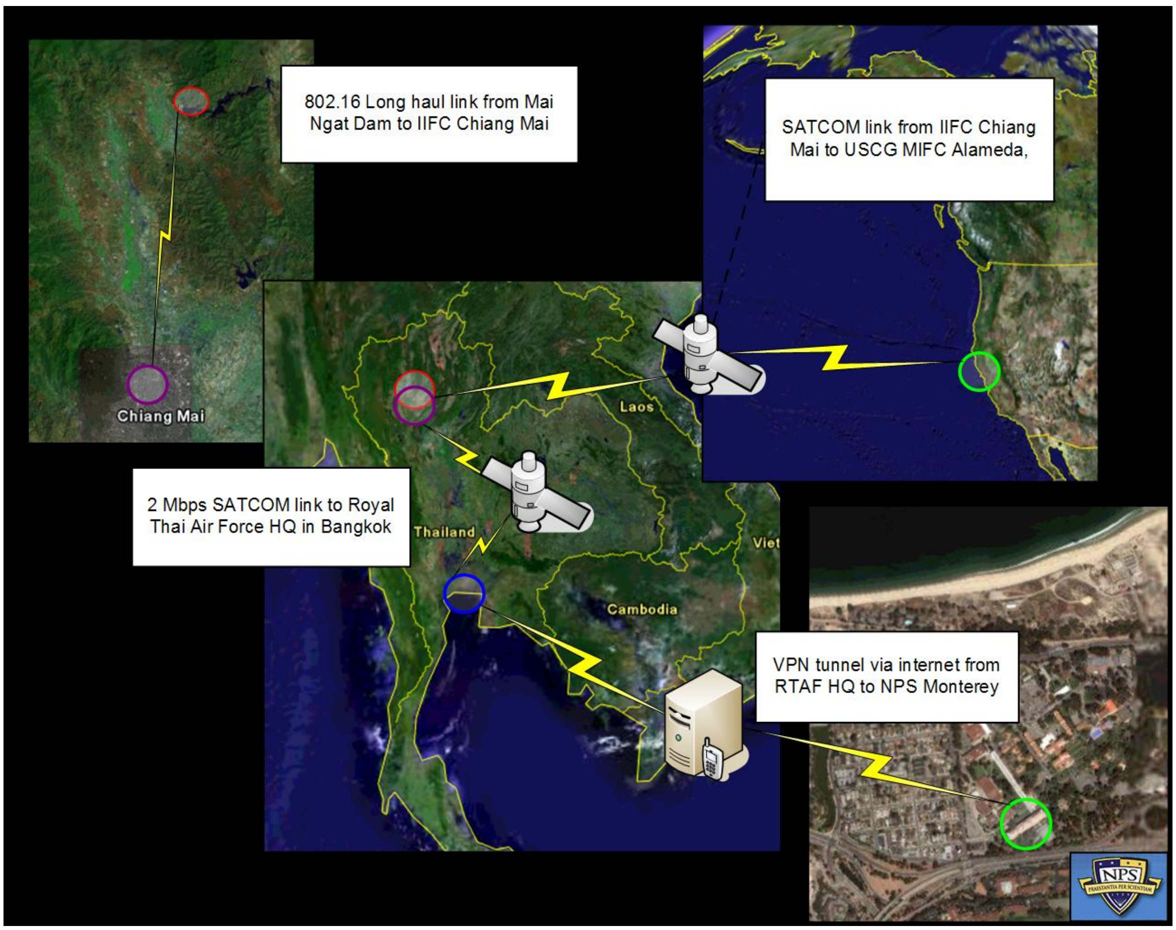

Figure 1. COASTS Global Topology

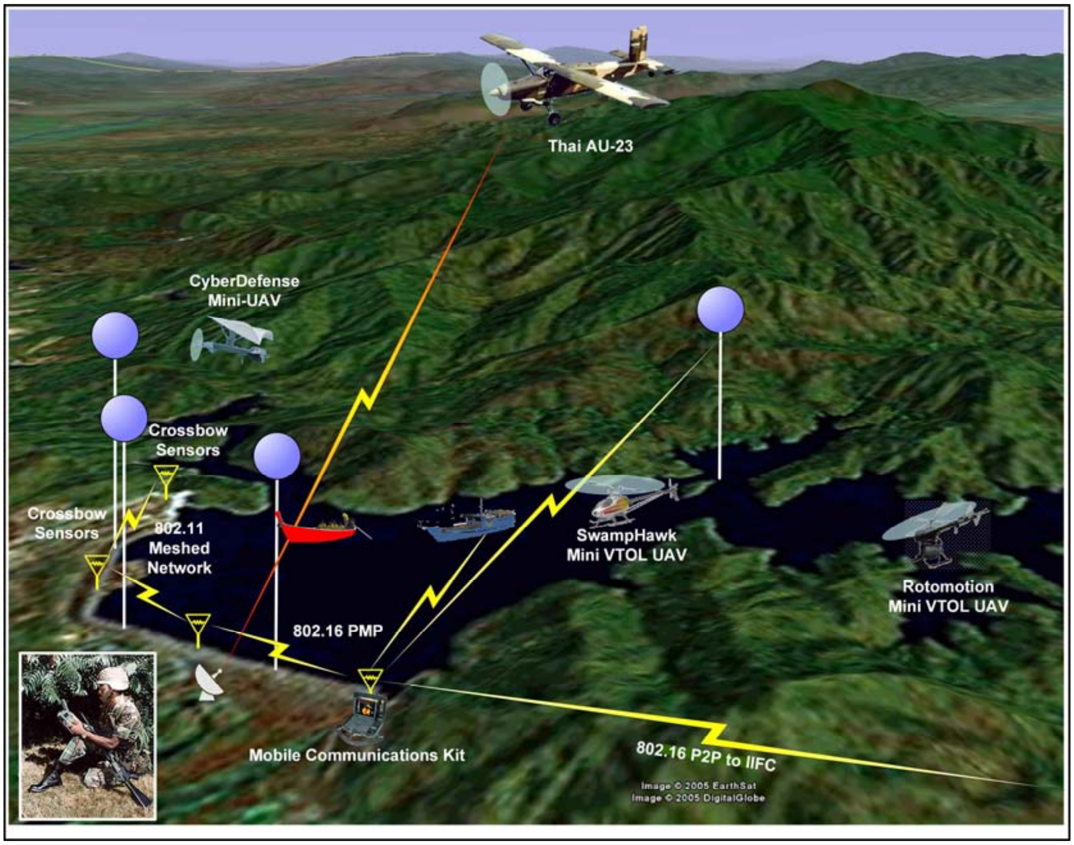

Figure 2. COASTS Scenario Topology

The topology is designed so that data and information can quickly and easily be relayed from the tactical area to the World Wide Web (WWW). The focus of this thesis will be solely on the scenario topology.

B. DESCRIPTION OF NETWORK ASSETS

The network had the following network assets employed throughout the testing phases that were carried out.

- Mae Ngat Dam Face
- Wing 41 Control Center
- Interagency Information Fusion Center (IIFC)
- Maritime Information Fusion Center (MIFC)

1. Mae Ngat Dam Face

The Mae Ngat dam was where the majority of the testing occurred. Through the use of various nodes at the dam, the mesh network was deployed. The specific nodes used were:

- Balloons
- 802.11 Ground
- 802.16 Point to Multi-Point
- Signal Denied GPS
- Sensor Nets

For each portion, or node, the respective networking configurations were applied that allowed each one to seamlessly join the network. Once connected, network testing and then mock scenarios were conducted at the dam site. The outputs of each individual node were accessible to any other element that was connected to the network.

2. Wing 41 Control Center

The Wing 41 Control Center was located at a Royal Thai Air Force (RTAF) installation in Chiang Mai, Thailand. The Control Center (CC) functioned as an overall commander for the specific battlespace, enabling the relay of information from the Mae Ngat Dam to the CC. Once the data and information had been sent, the commander at the CC could then analyze what specifically was occurring and provide feedback for the scenarios being played out at the Mae Ngat dam.

3. Interagency Information Fusion Center (IIFC)

The IIFC was also located in Chiang Mai, at a joint U.S.-Thai military intelligence location. Through a series of 802.16 Point to Point WiMAX connections the data being relayed from the Mae Ngat dam to the CC was also able to flow to the IIFC. The personnel at the IIFC could then see in real-time the events that were occurring at the dam face. In addition, the personnel stationed at the dam could communicate with those at the IIFC, relaying potentially important information back and forth along the communications chain.

4. Maritime Information Fusion Center (MIFC)

The MIFC was located in Alameda, California. Via the World Wide Web, the officers located at the MIFC were also able to track in real time what exactly was occurring at the Mae Ngat Dam. The data was relayed across the internet from the RTAF HQ in Bangkok.

While not functioning as a specific battlefield commander, the personnel in the MIFC were able to prove a specific concept of research, and could also simulate acting as an overall campaign commander. The instant real-time data provided valuable inputs from the specific battlefield, in this instance the Mae Ngat Dam. This idea of data relay can easily be visualized as covering more than one specific battlefield, hence providing the commander at the MIFC multiple real-time updates from several different battlefronts instantaneously.

C. BATTLEFIELD INFORMATION LIMITATIONS

The biggest issue that faces many combatant commanders is the lack of instant and accurate information regarding their specific battlespace. Through the integration of WLANs and mesh networking a more accurate picture of the battle can be drawn. The instant feedback potential that exists within wireless networking can provide the data needed to paint that highly accurate picture.

As shown through the various links (CC, IIFC, MIFC), a commander who has the overall battlefield picture can rapidly and effectively redeploy his units in a manner that can better combat the enemy. These links overcome the information limitations for the individual unit commander and provide a means for better utilizing his troops and combating the enemy.

III. 802.11 RADIO SIGNAL PROPERTIES

A. BACKGROUND

While this thesis does not intend to delve significantly into the different types of wireless networks that are currently available, some background and theory is provided for the user. The intention is to provide a brief knowledge base for understanding a wireless networking setup.

Since there are multiple types of 802.11 signals available for use (a, b, and g), the advantages and disadvantages of each were weighed to determine the best configurations for network deployment. The 802.11a signal operates in the 5.8 giga-hertz (GHz) radio signal spectrum, while 802.11b and .11g both function within the 2.4GHz spectrum.

B. TECHNICAL PROPERTIES

There are several differences that exist between the 5.8GHz spectrum and the 2.4GHz spectrum. In the 5.8 space, the use of orthogonal frequency-division multiplexing (ODFM) permits data transfer rates at very high speeds. When 802.11b was implemented it did not utilize ODFM, so it subsequently could not pass data at the same rates as 802.11a. However, when the newer standard of .11g was created, it too used ODFM so the higher speeds associated with 5.8GHz space could now be achieved in the 2.4GHz space.[4]

When the 802.11 signal standards were finalized by the IEEE, both the 5.8 GHz and 2.4 GHz spectrums were intended to be used for wireless networking, even more so after the advent of 802.11g. The 802.11a and 802.11g bands transfer data at practically the same rates and speeds. However, the higher frequency of the 802.11a signals yields a shorter wavelength than that of 802.11g.[5] Consequently the .11a signal is not capable of passing through objects

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[4] Jim Zyren, "802.11g Spec," *CommsDesign,* 01Feb2002, http://www.commsdesign.com/design_corner/OEG20020201S0035, (last accessed 15 March 2006).

[5] Related to the physics properties of radio signals, velocity = frequency * wavelength, with velocity being equal to the speed of light.

(walls, doors, etc) as readily or easily as the .11g signal, which in turn reduces the potential range of the signal. So, the commercial market began using the .11g signal instead of .11a in practically every indoor and outdoor network implementation.

With the entire commercial market essentially moving to the 802.11g space reduced the requirement of a network since only one standard was being used. Another advantage of using the 802.11g standard was the compatibility with 802.11b signal since the .11b and .11g signal share the 2.4GHz space. However, the 2.4GHz signal is an ideal range for most wireless devices, and has also been identified as a frequency range for scientific and academic research. As more and more products, ranging from mobile phones to microwave ovens in the 2.4GHZ band, are being made to operate wirelessly the chance for interference increases. The interference can affect the signal quality of the 802.11g signal, causing lower transmission rates and lost packets. In the worse case could completely break, or stop, the .11g signal. Conversely, since the 802.11a signal operates within the 5.8GHz space, it has less chance for interference since there are significantly fewer devices operating in that area.

C. THEORETICAL SIGNAL PERFORMANCE

If the 802.11 signal were tested in a vacuum, the speeds and data transfer rates that could be achieved would be at a maximum since no external interference would be present that could degrade the signal. Also, any attenuation and degradation effects from the signal spreading as it radiated would occur uniformly across the signal's range.

Also, due to the wavelength of the 802.11a and 802.11g signals (0.17ft and 0.41ft, respectively), the affects of fog, rain, snow, hail, and smog should be minimal, if any affect at all. The wavelength of each type of signal is long enough that it is appreciably longer than the size of a water droplet or smoke particle, so the signal should pass through those types of media without negative effects[6]. The 802.11 signal does not operate in a vacuum, however, and as a result the everyday operation of a network is subject to less than ideal performance.

D. COASTS IMPLEMENTATION

The advantage of the COASTS project was that it occurred entirely outside, free of obstructions experienced within an office or building. Both the 802.11a and 802.11g signals should perform almost identically. Since all of the client, or end user, devices were 802.11g, the coverage provided by the network had to be compatible with the user. The potential still existed that the .11g signal could experience some type of interference.

For the project, the Mesh Dynamics access points used were capable of being configured for both 802.11a and .11g. This permitted multiple configurations, and the final configuration was the use of .11a on the backhaul radios (each access point talking to each other access point), and the use of .11g for the service radios (talking to the end user on the ground). Since the range between the access points were greater than the range from an access point to a user, using the 802.11a signal reduced any chances for external interference than would occur with .11g, which would increase the reliability of the connections between the boxes.

[6] "Avoiding Static for Spread Spectrum" Tessco Technologies (2005). http://www.tessco.com/yts/customerservice/techsupport/whitepapers/spreadspectrum1.html (Last accessed 15 April 2006).

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IV. NETWORK CONFIGURATIONS FOR TESTING

A. 802.11 MESH TECHNOLOGY

The Wireless Fidelity (Wi-Fi) network provides connectivity for mobile clients both on the ground and in the air. Wrapped in a lighter package than other technologies, 802.11 provides the throughput required to utilize various commercial technologies such as voice over internet protocol (VoIP) and real-time video, as well as sensor to shooter and intelligence collection data.

The 802.11 mesh network technology was chosen for its advantages over alternate methods of wireless local area networking technology such as conventional 802.11, 802.16, and analog radios. In addition, the proliferation of commercially available 802.11-enabled clients makes the use of an 802.11 network almost mandatory. Specific advantages of an 802.11 mesh network include the following:

- It is self-forming and self-healing, unlike conventional 802.11.
- It has higher throughput, lighter pack weight and lower power consumption than analog radios.
- It has a smaller form factor[7] than 802.16.
- Lighter pack weight is ideal for balloon payload design.

1. Root Node

In a mesh network every node has the ability to act as a root node or any other intermediate node. This is the inherent self-forming aspect of the mesh technology. As such, if one node fails then any other can act as the root. Additionally, the reliability of the boxes permit multiple radio antenna configurations at each node which can optimize the data transfer rates.

[7] The usual definition of form factor is the physical size of the equipment. It can also include the power consumption and signal requirements. Compared to the 802.16 WiMAX signal, 802.11 requires significantly less power and takes up markedly less space. http://en.wikipedia.org/wiki/Form_factor, last accessed 25 April 2006.

For the COASTS project, the root node was the source of the signal for the rest of the nodes. The root node was hardwired via a CAT-5 Ethernet cable to the Tactical Operations Center (TOC). The TOC provided the signal to the root node which was then broadcast to the rest of the nodes in the network. As a result, an independent and free-standing network could be constructed and deployed. In addition, via the use of 802.16 WiMAX point to point relays, World Wide Web connectivity was provided that permitted users to surf the internet from the dam face if they were associated with the network.

2. Intermediate Nodes

Once the signal is routed through the root node, each intermediate node is able to associate with the network. The intermediate nodes extend the network footprint, increasing the range and area of the coverage provided by the network. In addition, each intermediate node acts as an access point, so the users can associate with any of the intermediate nodes and ultimately connect with the TOC.

In mesh technology, there can theoretically be an infinite number of intermediate nodes as they simply act as relays to pass the source signal downstream. The COASTS topology contained two intermediate nodes.

3. Final Node

In a mesh network, there is little difference between an intermediate node and a final node. A final node does not need to relay the signal any further, so its antenna and radio configurations may be slightly different. However, the final node still acts as an access point so it must be configured to allow users to associate with it.

B. PRE-DEPLOYMENT CONFIGURATIONS

Before the network configuration could be finalized for the Thailand deployment, testing was needed to determine the optimum design and setup. As such, several testing periods were conducted that helped illuminate which configuration to use. Each period was conducted with differing configurations, each building on the previous testing iteration with the goal of designing and ultimately deploying the optimal network.

1. Point Sur Naval Facility

The first testing iteration that was conducted for COASTS 2006 occurred at the old SOSUS facility at the closed Point Sur Naval Facility just north of Big Sur, California, in December 2005. The purpose of the testing was to establish a baseline for the network in terms of data transfer rates as well as garner ideas on how to configure the network. With the low amounts of humidity and moderate temperatures that were common around the locale, any impact that environmental measures might have on the network and the signal were expected to be at a minimum. As a result, a true indication of network performance could be interpreted from the testing.

Point Sur is a very small compound, on which the Naval Postgraduate School maintains some meteorological equipment. Because of its small size and its being on a sloping hill, it turned out to be less than optimal for testing the proposed 2006 topology. However, due to the lack of funding for the group to travel and flight restrictions in the area local to NPS, this was the only alternative that would allow unrestricted altitude deployment of the aerial nodes. COASTS members took this opportunity to become more familiar with the equipment as well as to begin testing. Consultation on 802.11 access point and antenna selection came from COASTS' cooperative research and development agreement (CRADA) partner Mercury Data Systems.[8]

For the specific data collection that occurred the antenna configurations in Figure 3 were used:

[8] 1LT Robert Lounsbury. "Coalition Operating Area Surveillance and Targeting System 802.11 Optimum Antenna Configuration" (2006) : 16-17

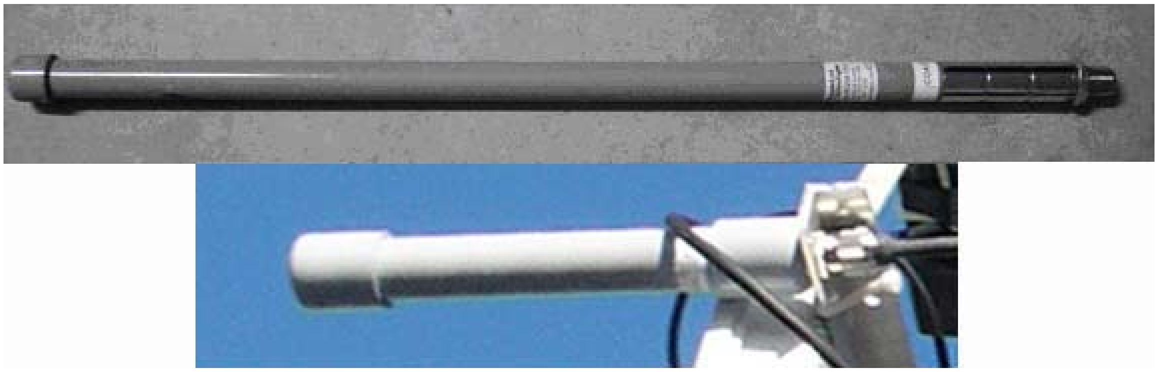

Figure 3. Backhaul Antennas Tested at Pt Sur
(Top Hyperlink 12dBi, bottom SuperPass 8dBi)

2. Fort Ord

The next series of tests were performed at Fort Ord, a former U.S. Army installation located near Marina, CA. Altitude at this location was more consistent, varying a maximum of eight feet: this was corrected for by changing the tripod height ensuring the antennas were closely aligned. The goal of this iteration was to highlight any difficulties in deploying the network as well as to test various aspects of the network.

Figure 4 shows the setup for the testing of the Hyperlink 5.8 GHz 12dBi omni antennas at Fort Ord, the same antenna introduced in Figure 3.[9]

[9] 1LT Robert Lounsbury. "Coalition Operating Area Surveillance and Targeting System 802.11 Optimum Antenna Configuration" (2006) : 19-20.

Figure 4. Fort Ord Antenna Setup

3. Fort Hunter Liggett

Fort Hunter Liggett (FHL), located approximately twenty miles west of Highway 101 near King City, CA, proved to be the best test location near the local Monterey area. A near-level tactical training runway gave the group a line of sight (LOS) range of roughly one mile. Testing was performed on the same antennas as Point Sur, shown in Figure 3. Again, these were the only available antennas in the COASTS inventory that were feasible for the COASTS 2006 topology. Figure 5 shows the complete setup of the proposed topology at FHL (less one aerial payload) as seen in the Mesh Dynamics Network Management System (NMS), Mesh Viewer. Throughput testing for ground to air was not accomplished, again due to the inability to physically connect a device to the aerial payload at altitude. In Figure 5, the final layout shows what the network engineers were able to demonstrate and that this concept can be implemented. Some of the antennas used in the ground to air nodes are depicted in Figure 6. Pictures and specifications for some of the actual antennas used in setting up the network depicted in Figure 6, specifically the 5.5dBi and 6.5dBi Hyperlink Technologies antennas used on Balloon 2, are not available on the manufacturer's website.

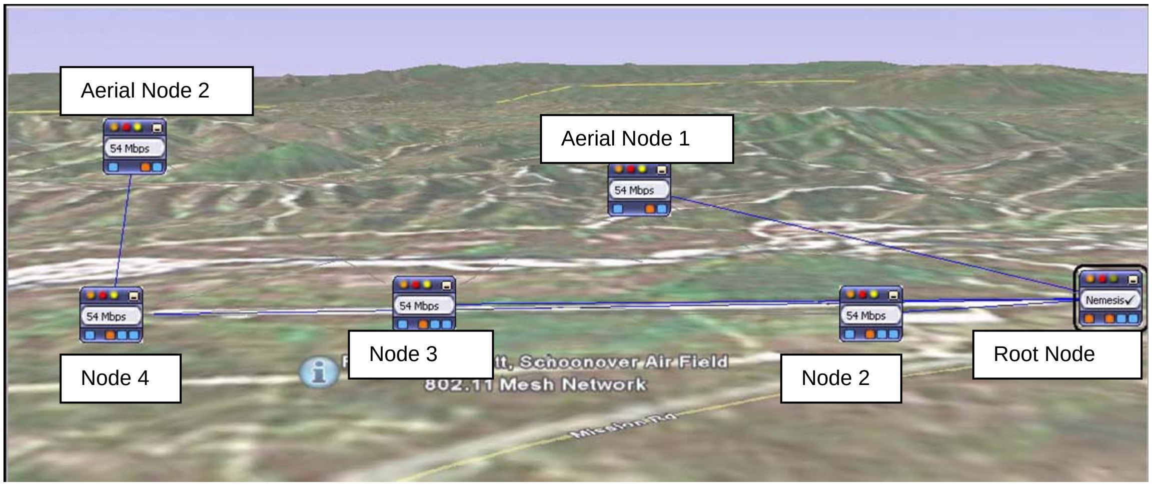

Figure 5. Fort Hunter Liggett Topology

Figure 6. Aerial Payload and Antennas

C. THAILAND GROUND NETWORK

For the network deployment in Thailand, the physical configurations were similar to what was tested in Fort Hunter Liggett. However, the physical distances that were covered on the dam face were quite a bit farther than what was tested in FHL. The physical distance between each individual node was approximately 0.3 miles, and the distance between the nodes allowed the footprint of the network to be extended considerably. Figure 7 shows the theoretical estimation of the network coverage provided in Thailand on the dam face. While the actual ranges varied, Figure 7 provides a general idea of network coverage which helped estimate network performance.

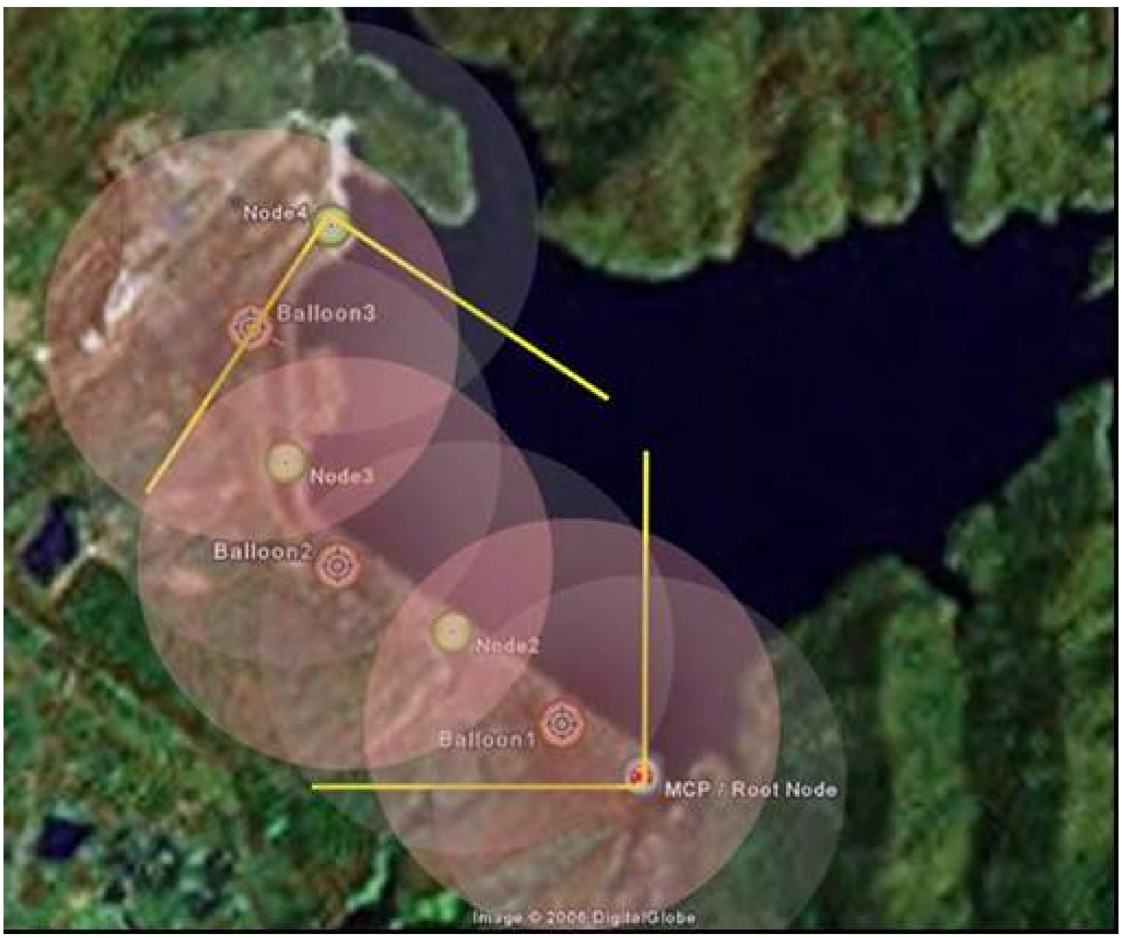

Figure 7. Ground Node 802.11 Mesh Network Coverage

1. Root Node

The configuration of the root node for the Thailand deployment was as follows (see Figure 8):

- MD4350-AAIx-1110 (Access Point)
- 13dBi MP 120°/90° Single Sector (2.4/5 GHz) Antenna
- 13dBi MP 120°/90° Scanning Antenna
- MP – Omni 5dBi5 antenna (2.4 GHz service)

Figure 8. Thailand Root Node

2. Intermediate Node Two and Three

The configurations for the intermediate nodes were as follows (see Figure 9):

Node Two:

- MD4350-AAIx-1110 (Access Point)
- MP – Omni 5dBi5 antenna (2.4 GHz service)
- 90^{o} Sector 13dBi Directional Antenna (5.x GHz backhaul)
- 90^{o} Sector 13dBi Directional Antenna (5.x GHz Uplink)
- UBI2590 Battery
- Necessary mounting brackets/hardware

Figure 9. Thailand Node Two

Node Three (see Figure 10):

- MD4350-AAIx-1110 (Access Point)
- MP – Omni 5dBi5 antenna (2.4 GHz service)
- 90^{o} Sector 13dBi Directional Antenna (5.x GHz Uplink)
- UBI2590 Battery
- Necessary mounting brackets/hardware

Figure 10. Thailand Node Three

3. Final Node Four

The final node is the concluding point in the mesh network. As it is the last node in the chain, it has a slightly different configuration than that of the rest to ensure good connectivity between the balloons and the rest of the nodes. The specific configuration for node four is:

- MD4350-AAIx-1110 (Access Point)
- 13dBi MP 120°/90° Single Sector (2.4/5 GHz) Antenna (Backhaul)
- 13dBi MP $120^{o}/90^{o}$ Scanning Antenna
- MP – Omni 5dBi5 antenna (Service)
- UBI2590 Battery
- Necessary Mounting Brackets/Hardware

The gain and antenna orientation is similar to that of the root node to ensure a significantly strong and wide signal will be present. This ensures good connectivity will be maintained with the rest of the ground and balloon nodes.

D. BALLOON NETWORK

The balloon payload is used in the COASTS project for two reasons. The first is so that it can extend the mesh network for greater coverage area for the network and client access. The second is so that it can carry a camera onboard which increases the slant range and field of view, which will allow personnel to visually track any incident that may occur. Positioning the camera on the balloon payload provides a higher position which in turn provides a greater area of coverage for visual target acquisition.

Since the payload is on a balloon the potential exists for a great deal of sharp, erratic movement which would degrade the 802.11 signal. As the video feed needs as much throughput as possible to provide a good, clear picture, several design configurations have been tested and the decision was made to utilize a 2.4 GHz service and backhaul radio to reduce the effects the movement might have. The balloon payloads are constructed as follows:

- MD4220-IIxx-0000 (Access Point)
- MP – Omni 5dBi5 antenna (2.4 GHz for backhaul and service)
- Axis 213 camera (For Video Surveillance)
- UBI2590 Battery
- 11.1 Volt Lithium-Poly Camera Battery
- Necessary Mounting Brackets/Hardware

In addition, the lines at the top and bottom of the payload were connected through a swivel and a windsock was attached. Both devices helped the payload shift into the wind which helped stabilize the image.

Figure 11 shows the topological network in Thailand and Figure 12 is the payload attached to the balloons.

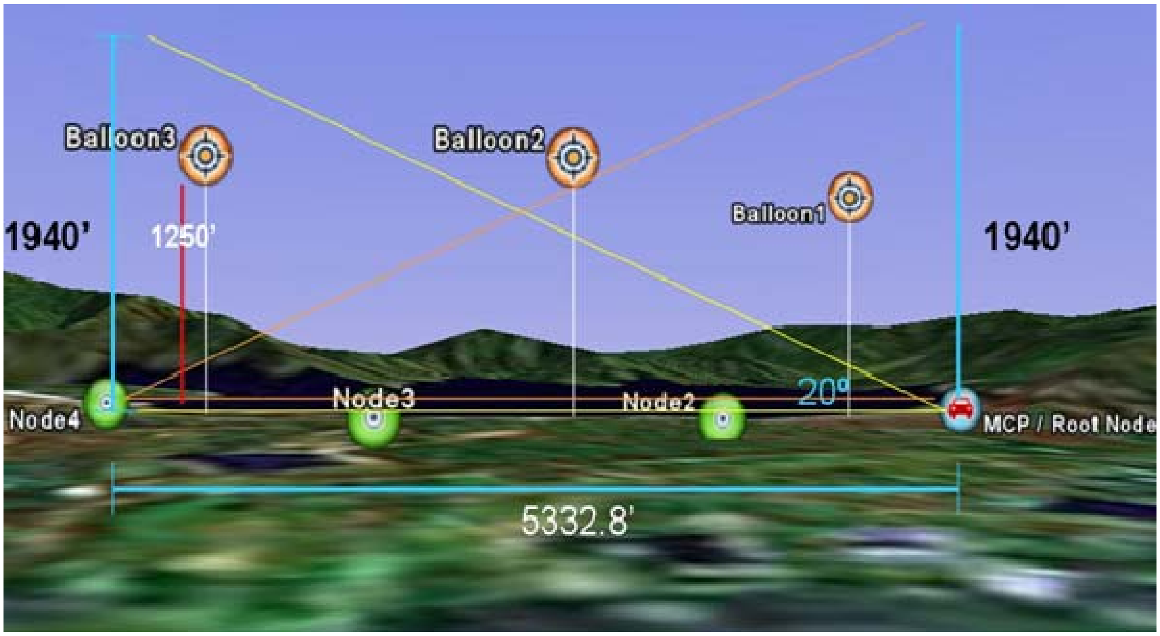

Figure 11. Balloon Backhaul Coverage


Figure 12. Balloon Nodes / Payload

E. REMOTE CLIENT

The final piece in testing the mesh network is having an individual client associate with the mesh. This enables connectivity from the network center through the mesh and ultimately terminating with the client. The hardware configurations used were:

- Dell D510 Laptop
- Proxim Orinoco Gold b/g Wireless Card
- 3dBi Rubber Bullet Multi-polar antenna

Figure 13. Remote Client

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V. DATA COLLECTIONS

A. IXCHARIOT CONSOLE

The network data that was collected for building the models consists of one main measurement, throughput. The other parameters recorded, transaction rate and response time, are directly related to the throughput of a network. Each parameter has a specific meaning for the network, but all are interrelated as they are all dependent on the quality of the signal as well as the signal to noise ratio (SNR).

Commercially available software has facilitated the collection of the network data. For each test run, the IxChariot console collects a minimum of one hundred data points for the various networking parameters and then performs statistical analysis on that data. The data is a time series, with the collections occurring sequentially from the beginning to the end of each test. The outputs provided are the maximum, minimum, average, and a 95% confidence interval for the average[10]. So, considering one test can take on average 1.5 minutes to complete, over the course of one day of testing for a network thousands of data points can easily be recorded.

Another advantage of using the IxChariot console is that the program has no inherent interest in any of the equipment being used. That fact is important because some manufacturers will overstate, or pad, their network data measurements so the performances appear better than they are. IxChariot provides that independent, impartial measurement so highly accurate results may be gathered.

1. IxChariot Endpoint

Even if the IxChariot console is used, data cannot be gathered unless there is another computer that can act as a remote client. The Endpoint is another program from Ixia that allows the IxChariot console to talk to that remote client. As

[10] "IxChariot User Guide" Ixia Corporation (2004) http://www.ixiacom.com (last accessed 8 June 2006)

such, the Endpoint program can be loaded on any desktop, laptop, or even a handheld pocket pc. That in turn allows the console and user to communicate so the various networking parameters may be recorded. The two internet protocol (IP) addresses are entered into the console and then the console runs specific scripts which allow traffic to be passed and records the statistics of the passed traffic.

B. KESTREL HANDHELD WEATHER STATION

For the environmental data gathered the Kestrel handheld was the primary source for data collection. A compact device that can fit into a jacket pocket, the Kestrel recorded the following metrics of weather data:

- Wind Speed
- Wind Chill
- Air Temperature
- Dew Point
- Barometric Pressure
- Wet Bulb Temperature
- Heat Index
- Altitude
- Density Altitude

The Kestrel is capable of storing 480 summary data points, with each summary data point consisting of the individual recorded data of each environmental parameter.

There were three different methods of weather data collections conducted. To garner an overall picture of what the daily weather patterns were, a Kestrel was mounted at the location of the root node. The collection interval was set at two minutes, which provided a sufficient range of data points for the entire day.

In addition, the remote client user carried another Kestrel with the laptop to take spot readings for an accurate reading of the specific location of the laptop. Finally, a third Kestrel was attached on the balloon payload so the environmental factors at an altitude of 2500 feet above ground level were recorded.

At the end of each day of testing and evaluation, the data was downloaded into a comma delimited file for ease of formatting and analysis.

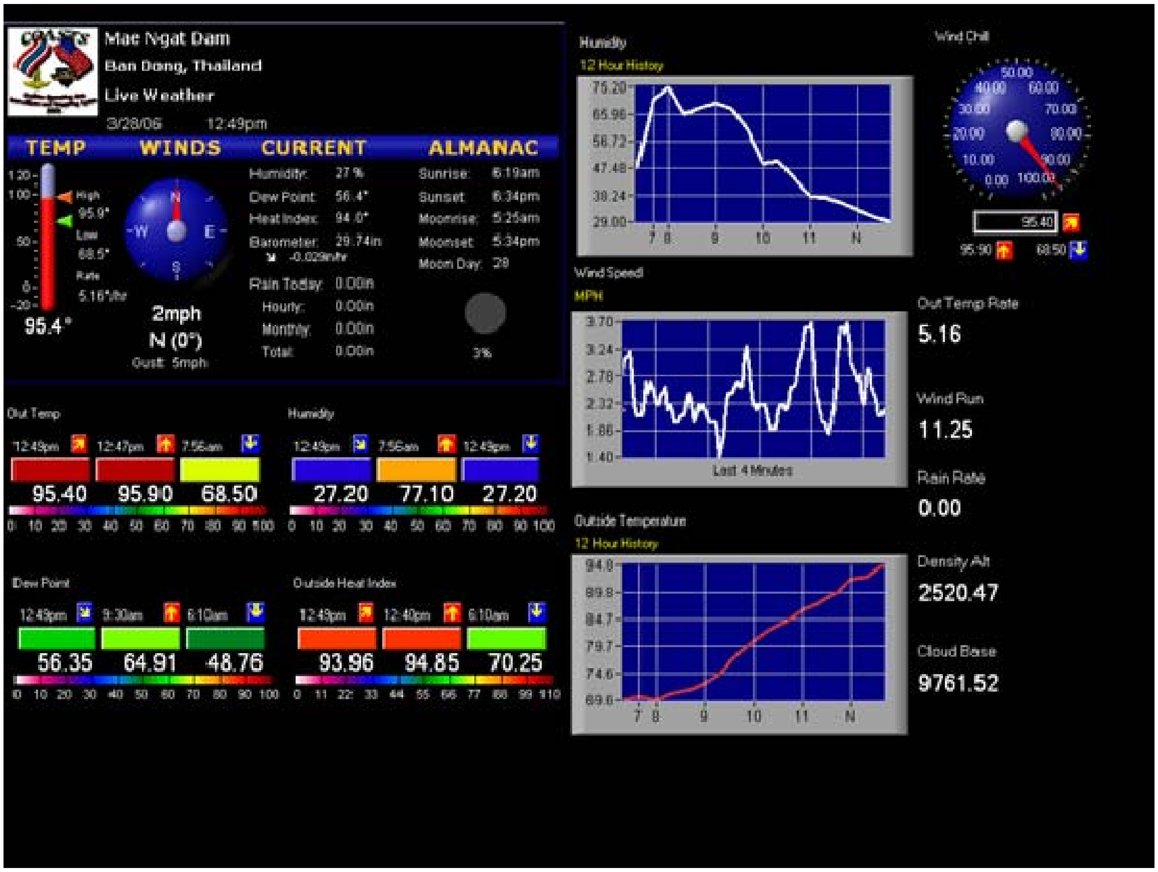

Figure 14. Kestrel Weather Station Graphical Interface

C. MESH DYNAMICS NETWORK MESH VIEWER

Another useful tool used for network monitoring was the Mesh Dynamics Network Mesh Viewer (NMV). Through the network interface, Mesh Viewer would analyze the network; gather information on all access points that were active and passing data, and report wireless signal strength in dBm, internal board temperatures in Celsius, and throughput in mega-bytes per second (Mbps).

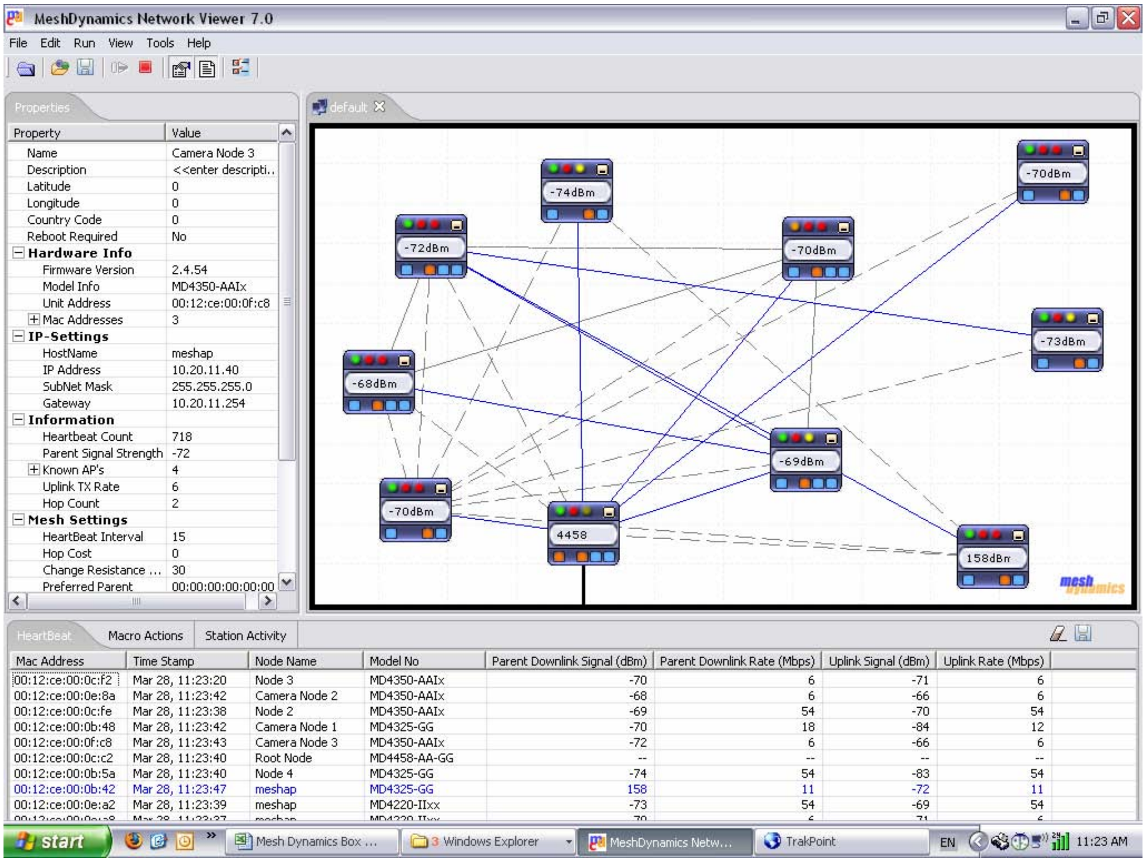

Figure 15. Mesh Viewer Screenshot

D. METHOD OF TESTING

The testing conducted consisted of a remote user taking a laptop or other enabled device and positioning the device in a specific predetermined location. Once there, the console then was configured for connectivity between the two. The next step was simply allowing the program to run and to collect the appropriate data. In addition, the environmental data was collected at each location.

The different locations tested different metrics at each point. Besides the network parameters, changing the location permitted the analysis that multiple hops through multiple nodes may have had on the signal. As a result, not only could the environmental issues be tested but specific network hardware configurations could also be examined.

E. 802.11 PARAMETERS

There are numerous measures of performance and measures of effectiveness that are associated with an 802.11 network. The first is simply the performance metric of the network. A metric can essentially be considered a score, so in that sense a larger score is better. Specifically for an 802.11 network a large metric for both throughput and coverage area is desired.

The performance metric should be proportional to the measured throughput. For example, if the throughput for one access point was exactly twice as large as compared to another access point, the metric for the first access point should be double that of the second access point. In addition, throughput should also be proportional to the coverage area. So, for the first access point, if it produced a throughput of 18Mbps over a specific area and the second access point produced 18Mbps but only covering half the area of that of access point one, then the metric (score) for the first is twice that of the second.

For the confidence intervals that IxChariot calculates, it calculates an estimated range of values using a method with a given high probability of 95% of covering the true population value.

The term probability in this definition points out the fact that IxChariot is doing a sampling of a real, finite, set of measurements. If the IxChariot console could sample all of the possible measurements of a network with infinite time and resources, it could be 100% sure that the calculated average is the correct value. Since IxChariot always generates a smaller-than-infinite set of measurements, some doubt as to how closely the sample average approximates the "real" average will always linger.

The confidence interval is calculated in the following manner:

- IxChariot first calculates the standard deviation of the measured time of the timing records.
- It then calculates the standard error, which is the standard deviation divided by the square root of the number of timing records, minus one.

- Next, IxChariot uses a t-table to look up the t value, using the number of timing records minus one.
- The confidence delta is the "t" value times the standard error.

The product is a confidence interval for the average measured time, which is used to display confidence intervals for the calculation of throughput.

The effect of the value t is such that the larger the sample size, the smaller the confidence interval, with all things being equal. Thus, one way to shrink the confidence interval is to have the pair generate more timing records.

It is possible to see a negative number in the lower bound of a 95% confidence interval. The statistical calculations being used assume an unbounded normal distribution, which could contain negative samples. In real life it is not possible to have a value of less than zero, since communications never go faster than the speed of light. Thus, if the IxChariot test gave a negative number on the left side of the interval then the legitimacy of the test would be in question.

The IxChariot console does these calculations internally and then displays the results in a convenient graphical user interface (GUI). Because the calculations are automatic, the time that would have been spent calculating the results were instead used to conduct additional tests.

VI. DATA ANALYSIS

A multi-scatter plot was used to visually assess any interactions between factors in a data set. Figure 16 plots pairs of the data from Thailand and Figure 17 plots pairs of the data from Fort Hunter Liggett (FHL).

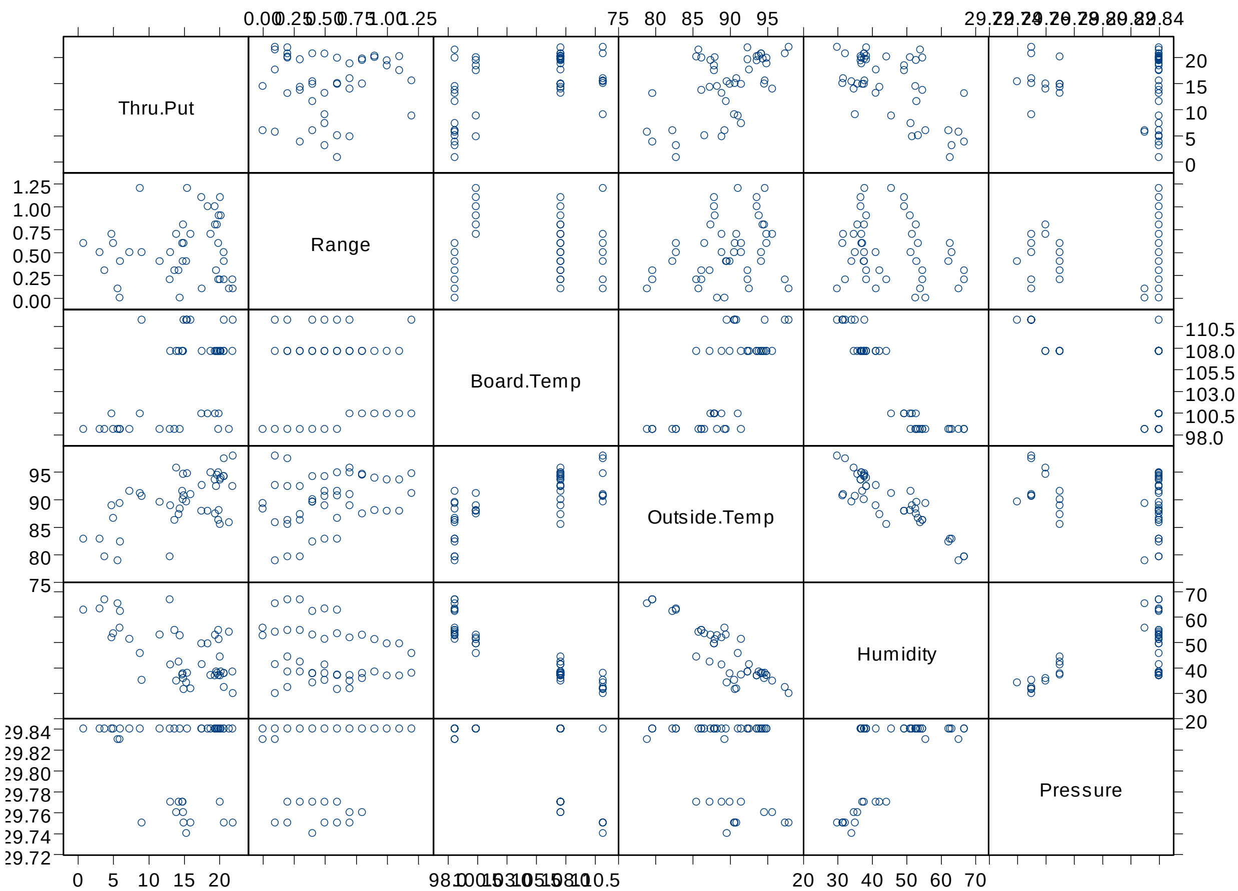

Figure 16. Thailand Multi-Scatter Plot

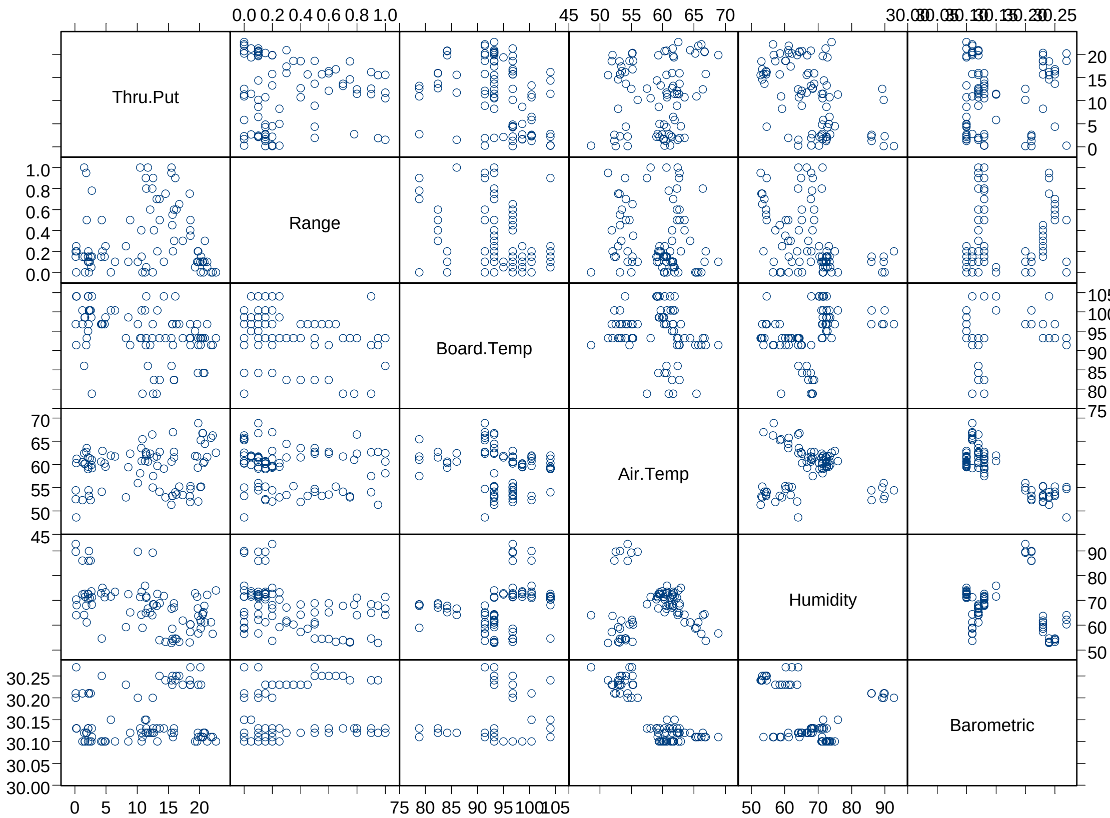

Figure 17. Fort Hunter LIggett Multi-Scatter Plot

From Figures 16 and 17, it appears that there are relationships between some of the different variables.

A. THAILAND ANALYSIS

From the multi-scatter plot in Figure 16, colinearity[11] is evident between the environmental factors. This is to be expected since, for example, humidity is strongly related to temperature, and even pressure. There are dependencies between all of the environmental factors, but the interest is in determining dependencies between throughput and any of the environmental factors, and if those dependencies cause a positive or negative effect on the network and throughput performance.

---

11 Colinearity is a measure of the dependence between the factors.

1. Humidity and Temperature Relationship

From Figure 16 it appears that the strongest relationship is between humidity and temperature. Further inspection seems to indicate that both temperature and humidity are associated with throughput. Figure 18 shows a clear linear relationship between temperature and humidity.

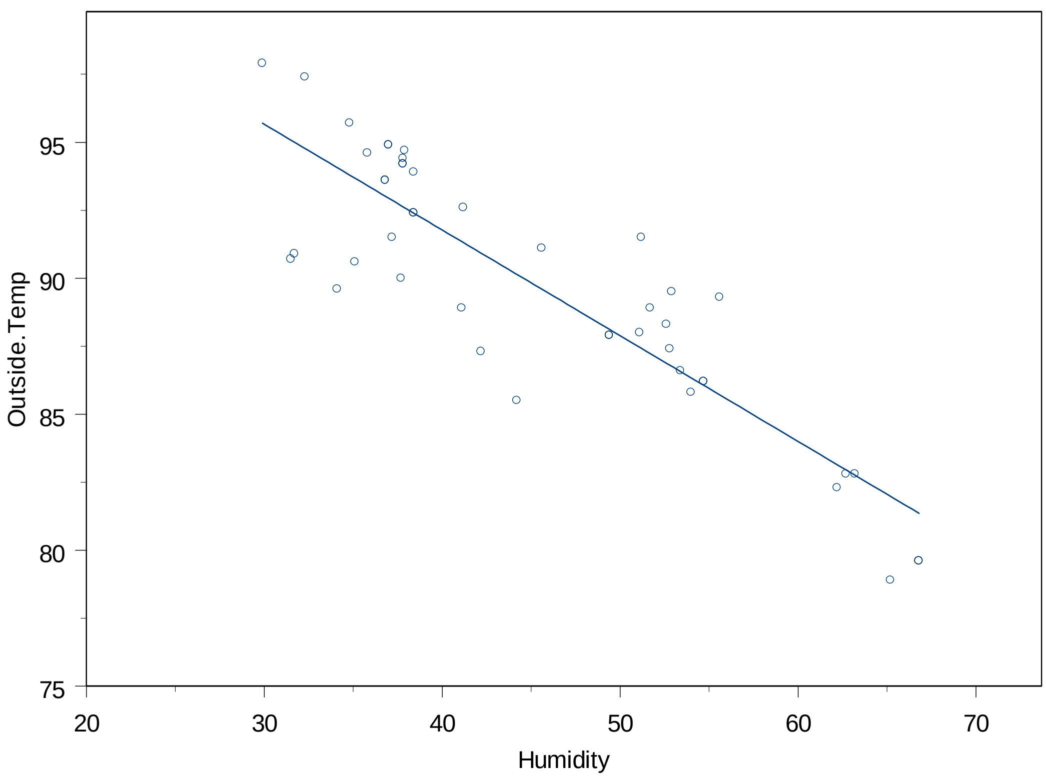

Figure 18. Humidity and Outside Temperature Relationship

A relationship appears evident, and to quantify that relationship a regression was conducted with humidity as the regressor and temperature as the response. An R-squared (also referred to as the coefficient of determination) value of almost 0.78 implies that 78% of the observed variation in humidity can be explained by differences in temperature. A regression with the factors reversed was also investigated but the results are quite similar, which verifies that there is a great deal of dependence between humidity and temperature regardless of how the regression is organized.

A brief digression into environmental characteristics at this point is required. Climatic research shows that humidity is generally higher during the early morning and late evening hours, which is the same time that temperature is generally lower. The transition between night and day and the addition of solar energy always plays an effect on how humidity and temperature respond. Since solar radiation excites the surrounding atmosphere the temperature correspondingly increases.

The increase in temperature causes the humidity levels to lower during the day, generally reaching the lowest point around 2:00 or 3:00 pm. It can be argued that temperature, in effect, drives the resulting humidity level. However, due to this inverse relationship, humidity and temperature have different effects on throughput. These characteristics were evident all throughout the testing that occurred in Thailand during the month of March. The conjecture is that temperature drives humidity, with higher temperatures resulting in measurably lower levels of humidity.

Since temperature drives humidity, the initial interpretation would be that temperature would provide the best indication of any effects on throughput. However, since temperature and humidity have a high degree of colinearity, either factor could be used to interpret any network response to a change in either temperature or humidity. The data would suggest that since humidity is driven by temperature, humidity would actually be a better predictor than temperature.

Visually, the relationships could be interpreted as Temperature » Humidity » Throughput. From this sequence, since humidity is “closer” to throughput, it provides a better indication of any effect on throughput. In addition, the R-squared value for the regression between humidity and throughput is higher, indicating a better fit, than the regression between temperature and throughput.

2. Humidity Effects

A regression was conducted on throughput with humidity acting as the regressor. From the regression there appears to be a decay of 0.347 Mega-bytes

(Mb) for each corresponding percentage point increase in humidity. The intercept is about 30.43 Mb. The maximum theoretical throughput experienced in a local 802.11 network is 54 Mb, however, lower throughput is understandable.

This regression has an R-squared value of about 38.3%. This could be better; so further investigation may be needed to determine if there are any added effects among the other environmental factors. Figure 19 illustrates the negative relationship between throughput and humidity.

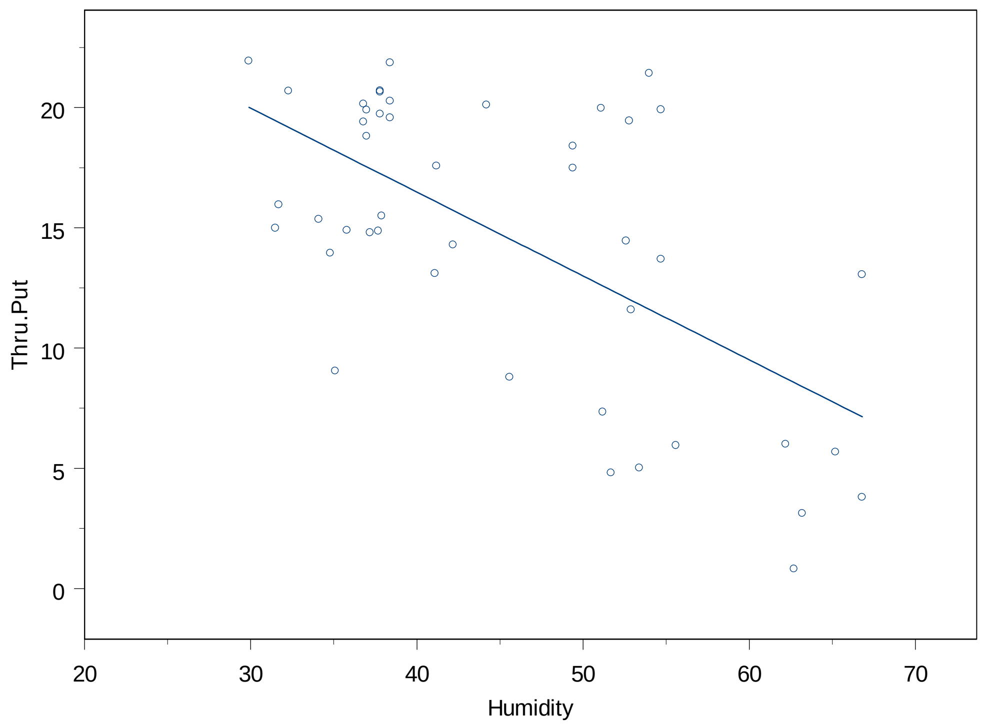

Figure 19. Linear Plot of Throughput vs Humidity

3. Humidity Residual Analysis

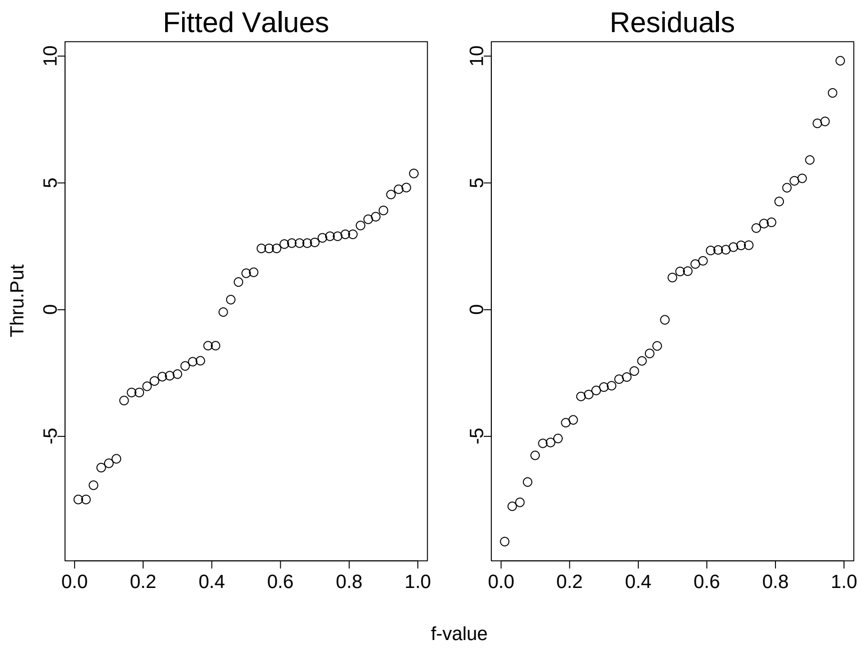

Figure 20. Residual Plot of Throughput vs Humidity

The residual plot in Figure 20 shows that the residuals are approximately normal. The residuals do not appear heavily tailed on either side of the data, so looking at the quantiles for the standard normal is needed for verification of the interpretation.

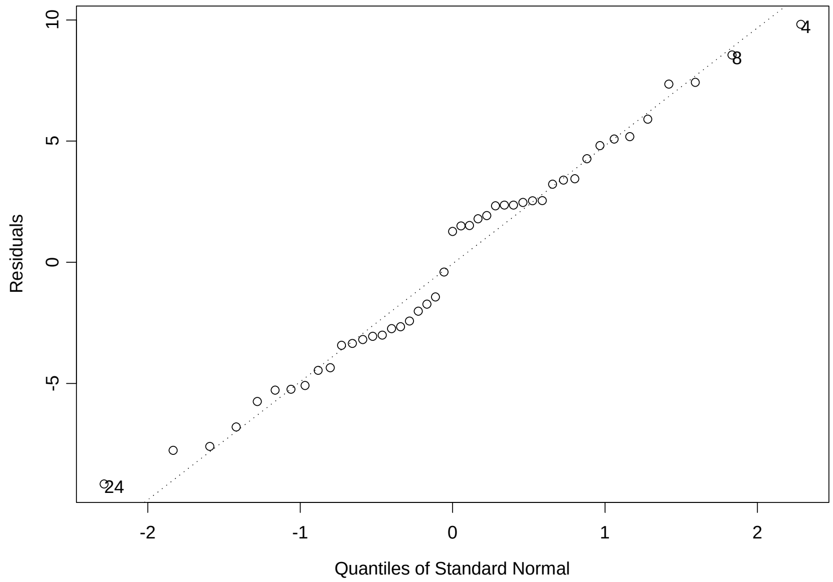

Figure 21. Humidity Quantiles of Standard Normal

Figure 21 verifies what was interpreted from Figure 20. As such, it would appear that humidity does not play a more significant effect at one end of the range than the other. For example, high humidity does not seem to affect throughput any more or less than how it affects it at the lower end. However, in this case, the highest humidity recorded during data collection was only 68.8%, which was not as high as anticipated. In actual field experiments, the data would seem to indicate that higher humidity would indeed affect throughput more severely. In other words, while the relationship appears linear over the range of the observed data, theory suggests a non-linear relationship over a wider range of humidity. Therefore, it is inadvisable to use the results of this analysis to extrapolate to more extreme levels of humidity.

4. Range Effects

When a network is being designed, the range of the network must always be taken into consideration, as a signal degrades the further it travels from the source. The question is if range plays a significant effect on any type of throughput degradation, since the access points were only separated by approximately 0.35 miles.

If the scatter plots shown in Figure 16 are analyzed, no relationship seems evident between range and throughput, indicated by Figure 22.

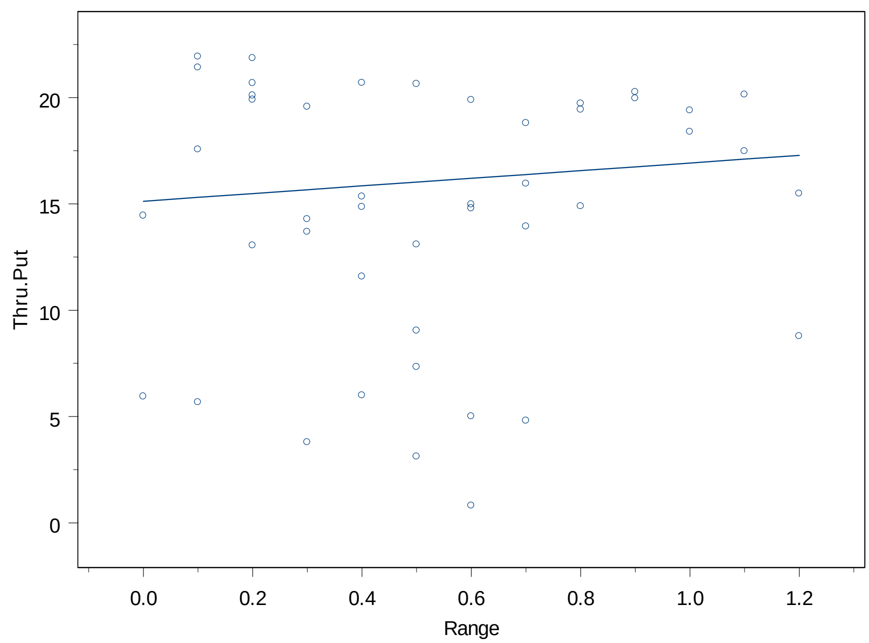

Figure 22. Throughput vs Range

Figure 22 shows the throughput slightly increasing as range increases, contrary to what the theory would predict. However, the variability is substantial, and this perceived relationship is insignificant. For confirmation, a regression was conducted between the two.

In the regression, the results show that range does not appear to act as a good predictor for throughput, as evidenced by its inconsequential estimated coefficient and its R-squared value of 0.006. That confirms what Figure 22 demonstrates graphically.

The explanation of why range is a poor *linear* predictor deals with the physical properties of antennas and how they radiate. For omni-directional antennas, which were used in the COASTS topology, as the signal radiates outward from the source the signal covers an increasingly larger area. As a result, the relationship is *non-linear*, and it can be visualized as starting at some constant value and then having an approximately exponential decay as range increases. Since the access points were relatively close and used higher gain antennas, the decay stayed close to the initial starting value, and consequently, little decay of the radio signal occurred.

5. Multiple Environmental Effects

After analyzing a few of the apparent factors from Figure 16, a model that interprets the influences of each of the environmental effects on throughput would be adequate. Pressure is not included in the regression as the range of values for pressure was very small, sometimes having an average change of only 0.02 to 0.05 inches of Mercury (in-Hg) throughout an entire day.

To confirm that humidity is the primary driver of throughput, comparing the predictive value of humidity compared to the predictive value of multiple factors may identify if additional factors are necessary. The full model consisted of throughput versus humidity, temperature, range, and board temperature. The reduced model consisted of only humidity.

The partial F-test yields an F-value of 0.5753, with a corresponding p-value of 0.6346. The F-value of less than one can be attributed to the fact that there is a high degree of colinearity between the factors, so the F-value of less than one is understandable. Most importantly, the partial F-test is consistent with the hypothesis that all factors *except humidity* are insignificant. Therefore, humidity in isolation provides an adequate linear model for the predicted throughput.

B. FORT HUNTER LIGGETT ANALYSIS

The data collected in Fort Hunter Liggett will be used for proof of concept and support for the Thailand data than for tangible results. The Kestrel weather handhelds were not in use in FHL, so the weather data that was collected was not at the same location that the network testing occurred. In the Central Coast region of California a difference of a few miles can cause large changes in the environmental factors. As a result, correlating the network data with the weather data was not as accurate as the Thailand data collections and analysis.

The micro-climate environment that is Central California did hamper the correlation of network data and weather data. Nevertheless, even though there was a higher degree of error in the data collections due to the variances in the weather, the data still indicated a strong relationship between humidity and throughput. While the R-squared values were lower, the analysis of the FHL data helped to strengthen the results from the Thailand analysis. In addition, the results from the FHL testing provided indications of what to expect when the network was deployed in Thailand.

C. FORT ORD AND POINT SUR DATA

The last two data sets, which relate to the first two testing evolutions, cannot, in the opinion of the author, be safely used to indicate any types of fit. Preliminary analysis on the data via regressions provided the highest R-squared value of 0.10, which included all factors acting as regressors. In addition, confidence intervals, while shown for the individual throughput data collected, could not be correlated to the weather data with any level of accuracy.

The lower values and poorer fit can be attributed to several reasons. For example, the weather data collected while in Fort Ord came from the Monterey airport, which was approximately fifteen miles away. Similarly while at Point Sur, the weather data collected was not local to the operating area.

As a result of the less accurate weather data, the Point Sur and Fort Ord testing acted more as a proof of concept testing evolution instead of an actual data collections and analysis situation. Based on this research, the network engineers were able to use the data from the IxChariot console to redesign certain payloads and antenna configurations, which in turn increased network performance. The “off the cuff” analysis helped provide a direction for the research.

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VII. CONCLUSIONS AND FUTURE RESEARCH

A. CONCLUSIONS

An 802.11 network, theoretically, should not experience any type of signal degradation when deployed, regardless of the environment it is deployed in and environmental factors that may be present. Since the signal is measurably smaller in physical size than smoke, fog, mist, or vapors, the signal should pass through the atmosphere without any loss or negative effects. As a result, the signal should only experience throughput degradation effects based upon the range of the network and the specific orientation of the antennas, and perhaps in the presence of moving water (rain, snow, or hail). However, the operational world is a drastically different entity than the theoretical world that exists within a laboratory or on the designing board. As such, external factors that would not be expected to have any interaction may indeed influence the 802.11 signal, which in turn would potentially reduce the expected throughput of the signal.

In the case of the COASTS 2006 network, the latter was indeed true. From the initial hypothesis testing the data seemed to indicate that the mean throughput recorded in Thailand was significantly different than what was experienced in Fort Hunter Liggett. What causes that difference is the question, since there should not be a difference between the two.

1. Humidity Effects

From the weather data collected, the maximum humidity that occurred in Thailand during the March testing never exceeded 68.8%. Interestingly, the highest humidity in Fort Hunter Liggett recorded during testing reached a maximum of 92.6%. In both data sets, the increase of humidity had a corresponding decrease in throughput. The decrease of throughput was approximately linear, and both data sets indicated an approximate decline of throughput at a rate of -0.35 Mbps for each corresponding point of increase in humidity.

The hypothesis testing indicated that the mean throughput was different at the separate locations, but the Thai data did not have any data points with the humidity above 70%, so it is possible that the humidity might affect the throughput more. However, considering the regressions from both data sets indicated similar types of fit as well as similar effects on throughput, it is safe to assume that the influence of humidity is similar regardless of location.

For the deployment of a network in a tactical environment, there can be anticipated decline of throughput as the humidity increases. Since the relationship between throughput and humidity does appear linear, if a network's expected use is in a high humidity environment, the expected throughput will be less than in a dry, low-humidity environment.

2. Temperature Effects

Temperature did not appear to reduce the potential throughput of a network to the same degree that humidity did. A correlation does exist between temperature and humidity but as shown in the data humidity plays a negative effect on throughput regardless of the temperature range. Inversely, when humidity is superimposed over the regression of throughput and temperature, humidity stills affects the network throughput greater than any effect that the specific temperature may have.

Temperature is directly related to the density of a fluid[12], so as a fluid's temperature increases, the density of that fluid decreases. In addition, as seen in the data, as the temperature increased there was actually a slight increase in throughput as well. The possible answer is that the less dense air, combined with the reduced humidity levels recorded at the higher temperatures, provided potentially fewer obstructions that might negatively impact the throughput. As a result, the network may actually perform better as the temperature increases. This is analogous with the predicted performance that personal handheld radio manufacturers (i.e., Motorola Talk-about) place on the rear of the packaging. The

[12] For this example, the term fluid references anything that is not solid and flows, which would include liquids and gaseous materials.

best performance can be expected in hot, arid, desert-like conditions, while the worst performance is in heavily wooded, urban, or poor weather environments, which are synonymous with higher levels of humidity and the potential presence of visible moisture.

So, regarding temperature, if a network is being planned for use in an arid, desert-like area such as the southwestern United States, then the performance of the network should not experience much loss of throughput, if any. In addition, if the temperatures that the network will experience are low, the throughput should still maintain consistency, as long as the relative humidity is low as well.

Unfortunately, there is one caveat to the explanation of temperature's effect on a network. The 802.11 signal does not merely exist in free space; instead, it must be put there by some type of electronic device. A basic law of electrical circuits and components is that as a device experiences higher temperatures, the internal resistance of that device will increase. As the resistance increases, the current will correspondingly decrease, in turn limiting the level of the signal that can be broadcast. This idea is discussed in Section 3 below.

3. Circuit Board Temperature Effects

Board temperatures seem to have a negative effect on the throughput of a network. Since resistance increases with temperature, the hotter a device gets, the greater the resistance, decreasing the level of current flow. Even though the Mesh Dynamic boxes were built to withstand high temperatures (approximately 75^{O}C), the increase in board temperature seemed to cause a corresponding decrease in throughput.

The recorded board temperatures for the Thai data were noted every thirty minutes, while testing occurred at any time. As a result, the test data was sometimes associated with board temperatures whose time-stamps were not very close. The board temperatures in the Fort Hunter Liggett data were recorded at the same time that a test was completed, which would explain the higher correlation coefficient between the throughput and board temperature in FHL.

The data would seem to suggest some type of relationship between an increase of circuit board temperatures and a decrease in network throughput. However, board temperature was insignificant in the presence of humidity. Further research would be needed to establish a relationship between the two.

4. Range Effects

While range is the ultimate limiting factor with any type of radio signal that is being broadcast, the COASTS network was not established to determine the maximum ranges possible. Instead, the ranges between the access points were set in a manner that extended the network footprint but was limited so the throughput would still remain constant and strong, disregarding any other limiting factors.

5. Pressure Effects

Pressure is one environmental aspect that did not appear to affect the network in any manner. Since barometric pressure usually remains fairly constant throughout the span of a day, there was never a large enough delta to correlate pressure with any apparent affect on throughput. For example, the data might range from 29.95 in-Hg to 29.97 in-Hg in one day. With a range of only 0.02, the pressure data could not provide a true indication of any response.

6. Final Conclusions

Taking into account all of the data and how the separate variables factored in, the greatest effect seems to come from humidity. If range were extended much further than what it was in the COASTS 2006 topology, then it too might account for a decrease in throughput. However, based on the strength of the radios and the antenna configurations, range did not seem to affect the network as much as the other environmental effects.

The predicted throughputs are listed in Table 3, as compared to the associated humidity levels. For humidity levels above 90%, there was one single observation to base the predictions upon, so the results are not accurate or confident. In addition, the board temperatures were not included since there were discrepancies in the data collections. For predicted throughput, however, humidity is the driving factor, if range is not being considered a factor as with the COASTS testing. As a result, the information in Table 1 and 2 and in Figure 23 and 24 will provide fairly accurate predictions for future network deployments.

For the values given in Tables 1 and 2, there is a difference in the predicted and average values at the 51-60% humidity level and the 61-70% humidity level. The explanation is that there were not as many observations at that range than at the other ranges. Increasing the number of data points would more than likely decrease the differences.

Humidity (%)	20-30	31-40	41-50	51-60	61-70
Average Throughput (Mbps)	21.93	17.546	14.835	13.049	5.401

Table 1. Average Throughput per Humidity Levels

Humidity (%)	20-30	31-40	41-50	51-60	61-70
Predicted Throughput (Mbps)	22.785	17.804	15.011	11.897	7.946

Table 2. Predicted Throughput per Humidity Levels

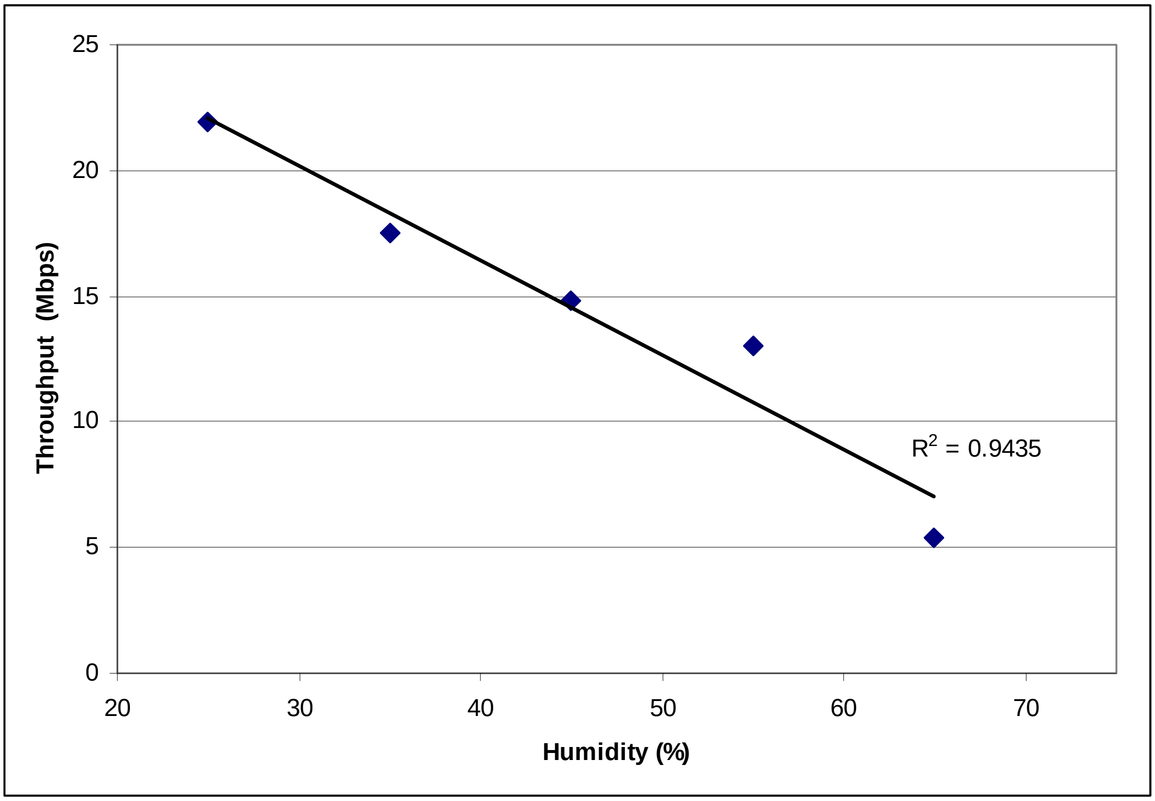

Figure 23. Plot of Average Throughput Values vs Humidity

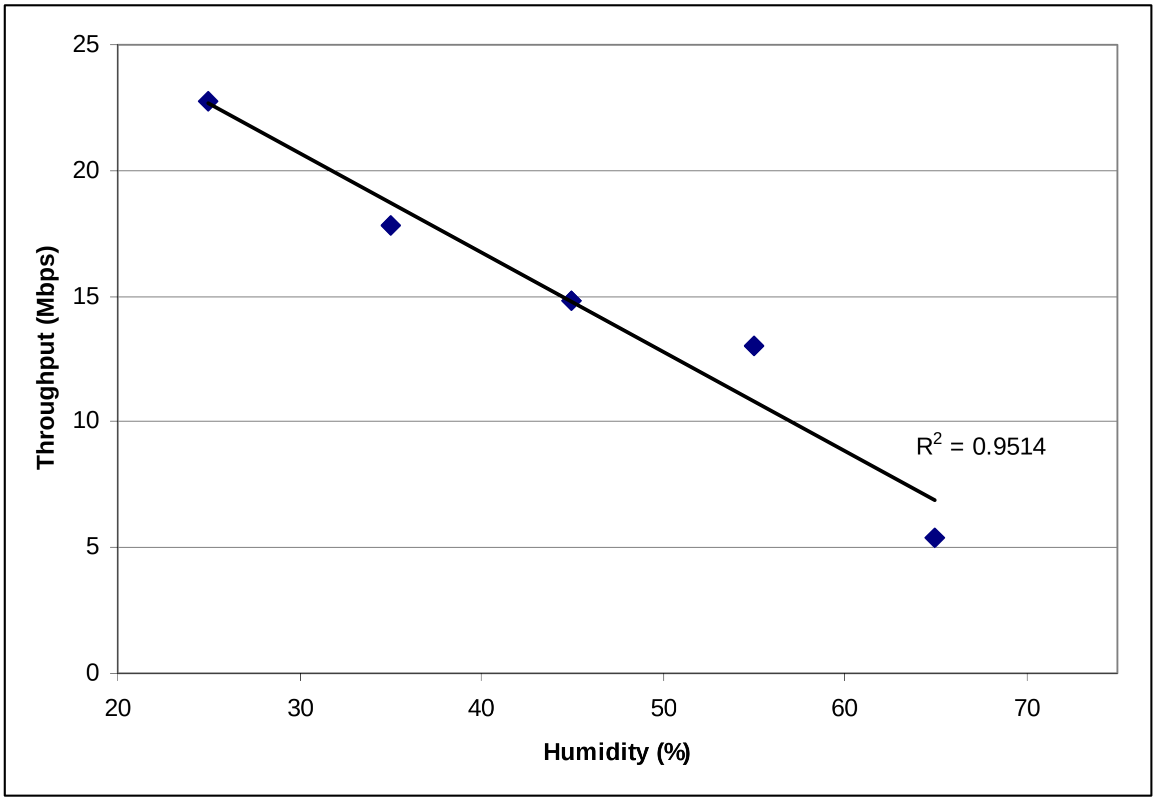

Figure 24. Plot of Predicted Throughput vs Humidity

While the graphs do not extrapolate into higher levels of humidity, the trend is that the throughput decreases with an increase in humidity. However, to positively confirm that effect, further research would be needed at those higher levels of humidity.

B. FUTURE RESEARCH AND ANALYSIS

While a great deal of data collection and analysis was conducted on the weather data and networking data, there were several areas that would benefit from further research and analysis.

1. May 2006 Thailand Data Analysis

To begin with, the data collected during the May 2006 testing iteration was not analyzed for inclusion in this thesis as time was a limiting factor for publication. As a result, the data from Thailand for the second testing iteration could be used to validate, or refute, the conclusions drawn from the first Thailand testing and the testing that occurred at Fort Hunter Liggett.

During the latter part of April and the beginning of May the jet stream in the lower to mid atmosphere (approximately 25,000 to 35,000 feet) begins to shift more towards the south of India, bringing a great deal of moisture from the Bay of Bengal and the Indian Ocean over the Indian subcontinent and into southeastern Asia. This climatic change is also known as the pre-monsoon, which is characterized by periods of intense rainfall and extremely high levels of humidity.

During the May testing, humidity was recorded at a maximum of 100%, without visible rainfall. In addition, temperatures again reached levels seen during the March testing (approximately 111 ^{O}F). As a result, the large range of humidity values might help provide another indication of any effect between throughput and humidity.

2. Internal Board Temperatures

Even though there was no apparent effect on throughput by outside air temperature, the high ambient environmental temperature in Thailand, combined with the heat produced by running electronics, produced internal temperatures that reached 54^{O}C, or 129^{O}F. Unfortunately, the time delta for board temperature observations was approximately 30 minutes. As a result, the correlation between a test that occurred at 1015 and a temperature measurement at 1030 was poor.

For future iterations of COASTS, recording board temperatures via a logging program or simply noting the temperature when a test is conducted would help prevent any poor correlation between board temperature and its effect on network throughput. In so doing, any relationship that might exist could be identified. That relationship, in turn, might help refine the throughput predictions given.

3. Ground Network Elevation Changes and Network Response

In the two testing iterations used for analysis, the ground network design consisted of nodes that were either at the same elevation or the difference in elevation was minimal. However, in an operational environment, flat or smooth terrain is not always present. Research that could include significant elevation changes on the ground network would help create a 3-D version of the 2-D ground network that currently exists.

4. Extreme Humidity Ranges

The data gathered for this thesis did have a few points that reached about 92%-93% humidity. However, there were very few points at that level which prevented a detailed analysis of the effects at a very high (>90%) level of humidity. The data from May plus additional testing may help identify any effects humidity might have on a network if the levels are at least 90% or higher.

5. Visible Moisture Testing

The final piece in evaluating how a network might perform would include testing the network while there is visible precipitation (snow, rain, hail, etc). Testing in a moderate climate such as Monterey does not provide much variation and Thailand was hot and humid but had little rainfall. A network that might be deployed operationally would only benefit from testing that would include every type of environmental condition expected.

6. Multiple Equipment Testing

The COASTS project only utilized the Mesh Dynamics access points. For a true indication of how an 802.11 signal might behave in the presence of varying environmental factors, varying the brand of access point will strengthen the results since doing so would avoid any inherent biases from using one sole source of equipment.

C. RECOMMENDATIONS

During the COASTS 2006 project most of the data collected occurred in clumps, usually around 10:00 am and then again at about 3:00-5:00 pm. Future iterations may benefit from having multiple testing times, which should range from the earliest moment the mesh network is powered on to various times throughout the day. In addition, the IxChariot console should be located on a laptop or console that is not the main networking control console. Plus, having at least two IxChariot consoles available would expand testing possibilities. The mesh type network is designed such that traffic passing through the most distant node should not interfere with traffic passing through the root node. As a result, multiple and independent testing would help increase the number of data points as well as provide separate data sets which could help strengthen any conclusions.

For the data analysis, using the data parsing program that was written by LCDR Mike Schimpf will drastically reduce the organization portion of the program. As a result, future analysts can spend more time analyzing the data and less time simply sorting through it, which in turn will allow more in depth analysis of the data collected.

In summary, the COASTS program is furthering research with cutting edge technology in environmentally hostile areas. Data collections and analysis will continue to help support the research being conducted by answering the questions that the network engineers are posing. Future iterations will only build upon and refine the work that has already been done.

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